Discussion Paper #6

Use of Volume/Capacity Ratio Versus Delay for Planning and Design Decisions for Signalized Intersections

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The concepts of capacity and level of service are important for analysis of signalized intersections. For signalized intersections, capacity and level of service are analyzed differently because they are defined based on different criteria. The capacity condition for an intersection is defined by a composite volume/capacity ratio for the critical lane groups for the intersection. The capacity for the entire intersection is not explicitly defined. The level of service is based on the average stopped delay per vehicle for the traffic movements in the intersection, because delay is accepted as the best measure of quality of service to users.

Composite of V/C Ratio

Thus, the volume/capacity ratio measure can be assumed to measure capacity sufficiency and delay is a measure of the quality of service.

Capacity is analyzed for each lane group entering the intersection. The capacity for each lane group is

$$C_i = S_i \, (g_i / C) \qquad (9\text{-}3)$$ [1]

where

C_i = capacity for a lane group I, vph

S_i = saturation flow rate for lane group I, vphg

g/C = effective green time over cycle time ratio

The saturation flow is the maximum flow rate that would occur if the traffic stream was flowing smoothly and was not interrupted, according to the new 1994 *Highway Capacity*

[1] Equation numbers from 1994 *Highway Capacity Manual.*

Manual (HCM) about 1900 vehicles per hour of green. The v/c ratio is the volume for the peak 15 minutes divided by the capacity of the lane group. Although the capacity for the intersection as a whole can not be defined, a composite v/c ratio can be defined by summing the v/c ratio for the critical lane group.

This is the critical v/c ratio, designated as X_c. This can be calculated from the equation

$$X_c = \Sigma (v/s)_{ci} [C/(C-L)] \tag{9-5}$$

where

X_c = critical v/c ratio for the intersection

$\Sigma (v/s)_{ci}$ summation of the flow ratios for all critical lane groups I where v = demand volume and s = saturation flow for each critical lane group

C = cycle length (use maximum acceptable)

L = total lost time per cycle

The volume to capacity ratio for the intersection X_c, can be employed to indicate the adequacy of the intersection geometry and capacity as needed for planning. This volume/capacity ratio measure of capacity sufficiency of the overall intersection is a good indication of whether the physical geometry design features and the signal design provide sufficient capacity for the intersection, according to the 1994 HCM.

1994 HCM Planning Procedure

The new 1994 update to the HCM approach for signalized intersection capacity analysis for planning and design decisions that uses the critical volume/capacity ratio for the critical approach volumes. A level of service can not be determined from the HCM planning capacity analysis results, however, the expected operational status is expressed as “over”, “at”, “near”, or “under” capacity. This is a defaulted version of the method for operational analysis.

Table 1. Intersection Status Criteria for Planning*

Critical v/c Ratio x_{cm}	Capacity Condition
$x_{cm} \leq 0.85$	Under capacity
$0.85 < x_{cm} \leq 0.95$	Near capacity
$0.95 < x_{cm} \leq 1.00$	At capacity
Xcm > 1.00	Over capacity

* Based on Table 9-14, 1994 HCM

Delay Measure

The delay incurred by drivers is used to define the level of service for signalized intersections since it reflects drivers discomfort, frustration, energy consumption and travel time. The average stopped delay per vehicle in the peak 15 minutes is the criterion used. This is a complex measure and requires analysis using a number of variables, including the cycle length, phasing spits, quality of progression and the v/c ratios for the lane groups. Other basic information on the intersection geometrics, lane utilization, movement volumes, left turn treatment and parking conditions on each approach is required in the operational analysis method.

The operational analysis criterion considers the full details about the demand volumes, intersection signalization, intersection geometric design and the delay to analyze the quality of operations. It is therefore very appropriate for optimizing and evaluating the operational characteristics of an existing intersection, or group of intersections including cycle length, phase splits, phasing pattern and coordination.

The delay criteria should not be used in determining the level of performance for planning and design decisions because numerous factors including traffic demands, heavy vehicles, parking conditions, arrival type, cycle length, and phasing pattern influence the intersection performance. Further, the theoretical delay equation includes terms to evaluate uniform delay and random delay, as well as calibration terms to match actual experience at research sites. This equation could be similarly calibrated to each locale to assure that local conditions are matched. The delay equation is a complex, highly non-linear equation that includes a number of variables, most notably the volume/capacity ratio for the lane group. The following equation is quoted from the 1994 HCM update:

$$d = d_1 DF + d_2 \qquad (9\text{-}23)$$

$$d_1 = 0.38C\,[1 - (g/C)]^2 / \{1 - (g/C)\,[\mathrm{Min}\,(X, 1.0)]\} \qquad (9\text{-}24)$$

$$d_2 = 173X^2\,\{(X - 1) + [(X - 1)^2 + mX/c]^{0.5}\} \qquad (9\text{-}25)$$

where

d = stopped delay, sec/veh;

d_1 = uniform delay, sec/veh;

d_2 = incremental delay, sec/veh;

DF = delay adjustment factor for quality of progression and control type;

X = v/c ratio for lane group;

C = cycle length, sec;

c = capacity of lane group, vph;

g = effective green time for lane group, sec; and

m = an incremental delay calibration term representing the effect of arrival type and degree of platooning.[2]

Comparison of the HCM Planning and Operational Analysis Procedures

Approximately 200 separate runs were made of typical intersection conditions using both the 1994 Highway Capacity Analysis Planning procedure and the Operational Procedure. A number of intersection scenarios were defined with assumed geometric design, traffic volume and traffic control data. A run of each scenario was made to obtain the planning capacity condition and the intersection volume/capacity ratio. All were found to be "under capacity" (Σ v/c = $X_c \leq .85$) and "near capacity" (Σ v/c = X_c .85 to .95) by the planning analysis. Each scenario was then modified by changing variables that could be altered in the operational method to improve operations, such as cycle length, phasing pattern, phase splits, arrival type and parking condition. The range of levels of service resulting was 2 to 4 levels, typically from "C" to "F". This shows how important operational, temporal conditions are to the quality of the performance. It also shows that if the capacity is provided, a traffic control condition can typically be found to provide a good level of service.

A study done by Mark Virkler[3] et al. also showed the consistency of the volume/capacity measure the variability of delay measures at intersections. Figure 1 shows a comparison of the composite intersection v/c ratios for intersections with the HCM timing pattern and the actual timing pattern. The composite volume to capacity ratios for the intersections from the

[2] 1994 Highway Capacity Manual Update, TRB, Washington, DC.

[3] Mark R. Virkler, et al., A Comparison of the HCM Planning and Operational Analysis Procedures for Signalized Intersections," a paper presented at TRB, Washington, DC, 1996.

HCM and actual are nearly equal, shown by a slope of 1 for the line through the data points.

In Figure 2, a comparison is made between the delay with the HCM timing plan and the actual timing plans. The scatter of points demonstrates the discrepancies between the delay estimates based on the HCM operational analysis and the actual timing. Also, there were 22 cases, nearly 13% of their sample that could not be reported because a lane group volume/capacity was too high for the delay equation to be appropriate.

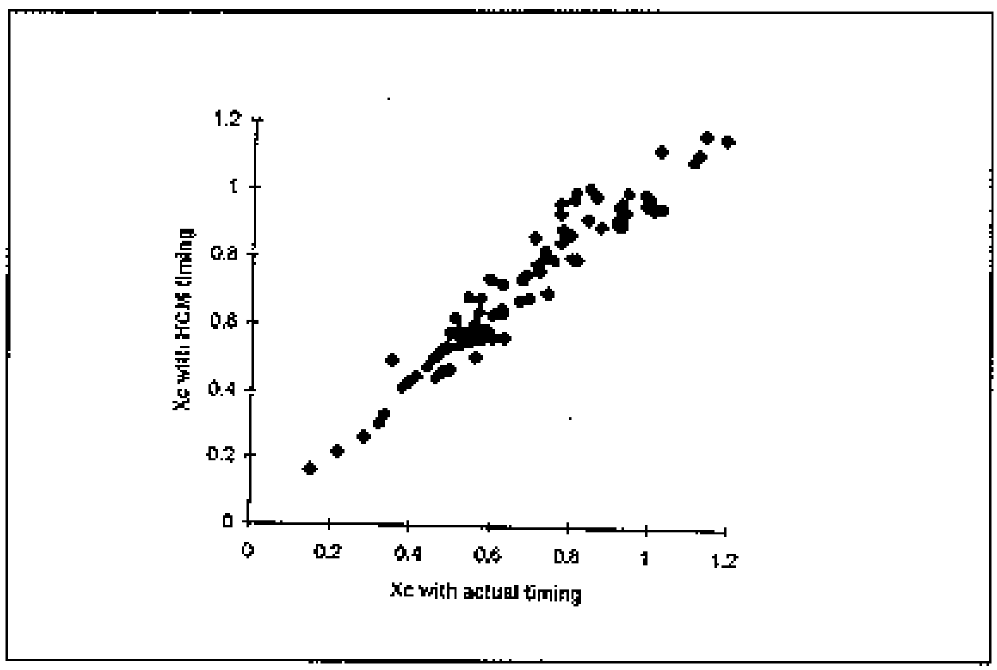

Figure 1. Comparison of Xc Values for Actual Timing vs. HCM Timing

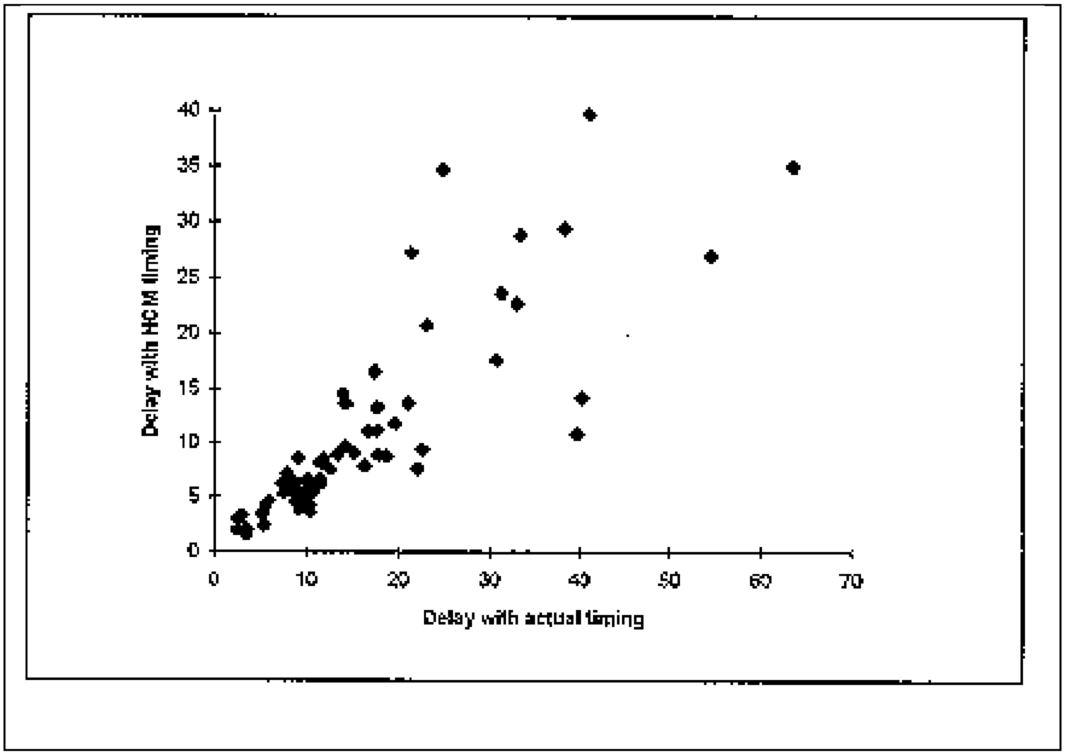

Figure 2. Comparison of Average Intersection Delay with the Actual Timing vs. HCM Timing

The 1994 HCM recognizes the variety of factors influencing the delay and the inappropriateness of delay as the criteria for planning and design decisions, as follows:

> "Level of service is based upon the average stopped delay per vehicle for various movements within the intersection. Although v/c affects delay, there are other parameters that more strongly affect it, such as the quality of progression, length of green phases, cycle lengths, and others. Thus, for any given v/c ratio, a range of delay values may result, and vice versa. For this reason, both the capacity and level of service of the intersection must be carefully examined.
>
> The v/c ratio is a measure of capacity sufficiency, that is, whether or not the physical geometry and signal design provide sufficient capacity for the subject movement or movements. Delay is a measure of quality of service to the road user. Both must be analyzed to fully understand the anticipated operational characteristics of the intersection, and neither can be substituted for the other. As a practical matter, however, it must be recognized that an intersection cannot operate beyond its capacity indefinitely without experiencing excessive delay.
>
> For planning purposes, it may be more appropriate to consider the provision of adequate future capacity as related to geometric design features. Delay may be less of a concern, because it may be improved significantly through coordination of signals and improved signal design.[4]

In summary, delay is not appropriate for planning and design decisions because of the extensive requirements for detailed current data, the complexity and non-linearity of the

[4] 1994 Highway Capacity Manual Update, TRB, Washington, DC.

delay equation, and the lack of calibration to local conditions. The volume/capacity ratio is a measure of the capacity sufficiency. And, according to the 1994 Update to the Highway Capacity Manual, for planning purposes it is more appropriate to consider the provision of adequate future capacity for decisions on geometric design features.